# *RER-3D: A Research Center for Radiation Effects Reliability Mechanisms Unique to 3D Integration*

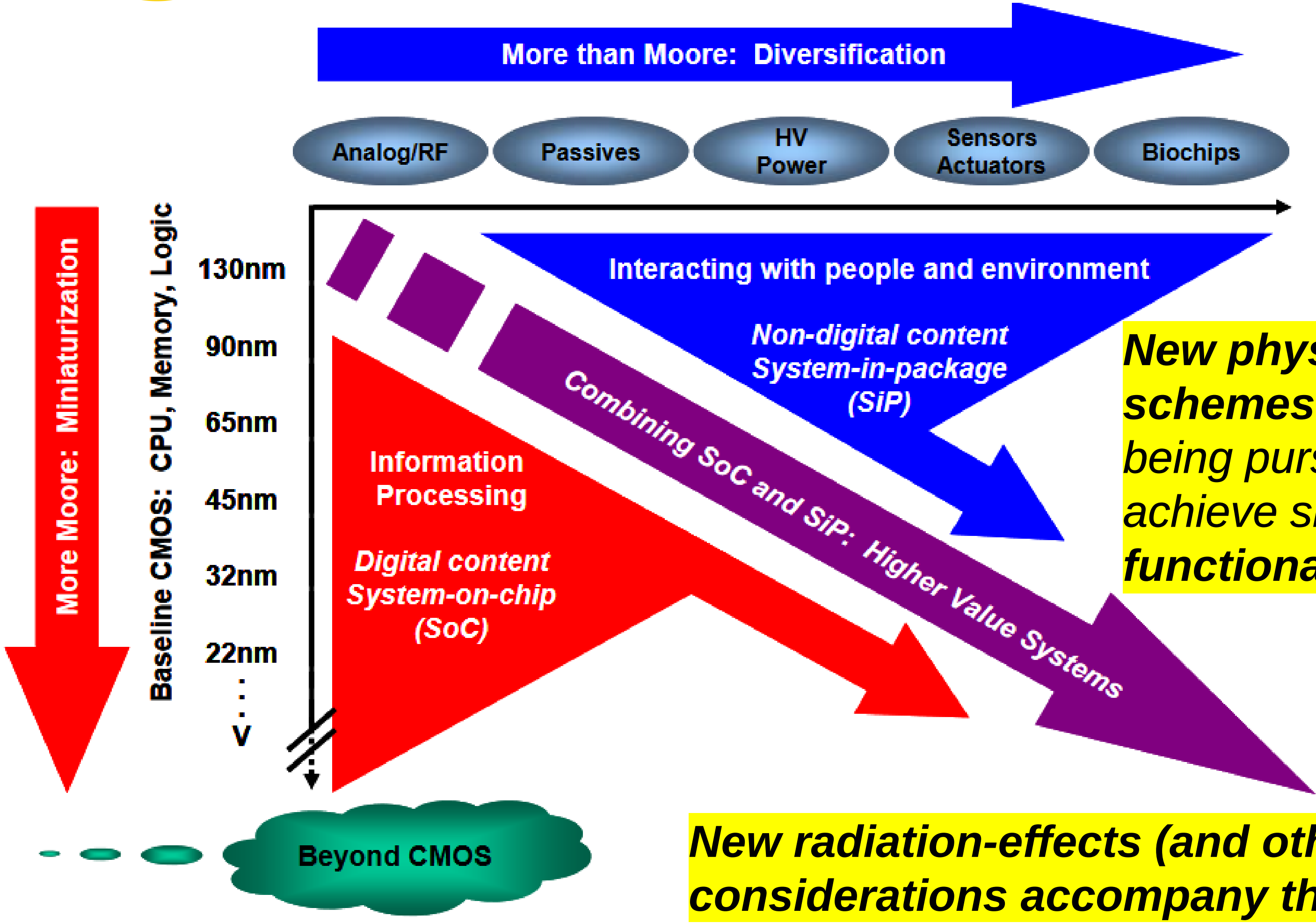
**Vanderbilt, UCLA, NCSU, Aerospace, imec, cea-LETI, NHanced**

**Grant # HDTRA 1-18-1-0002**

# Team

- UCLA Center for Heterogeneous Integration and Performance Scaling (CHIPS)
- NCSU previous and existing synergistic programs
  - Several 3D integrated circuits previously designed and fabricated
  - Other designs / fabs in process and planned
- Industry leaders in 2.5D/3D integration development
  - Nhanced Semi, imec, cea
  - Provide access to a range of test modules and integrated functional parts
- Unique radiation effects testing, modeling, and analysis expertise
  - Vanderbilt, Aerospace Corp.
  - Custom radiation transport codes
  - Unique pulsed X-ray test capability (among many available sources)

# Motivation

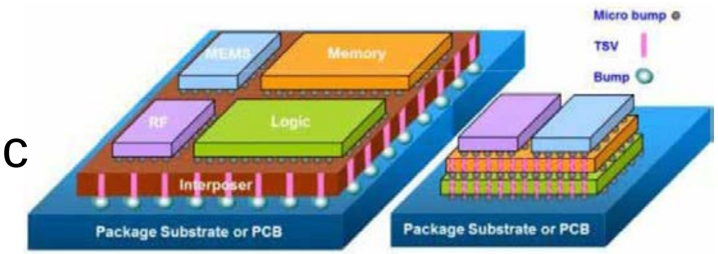



***New physical integration schemes** are required and being pursued to (profitably) achieve smaller, more efficient **functional systems***

***New radiation-effects (and other reliability) considerations accompany the new schemes***

# Integration Schemes

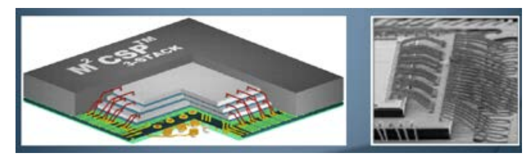
- Integration options at different levels:
  - Packaging, wafer/die stacking, monolithic
  - Many custom options, evolving process
  - Approaches are application driven
  - COST, COST, COST
  - *Near term: How do we “slap together” the needed components to achieve a function*
  - *Longer term: High-value, or low-cost, opportunities for more intimate integration schemes*

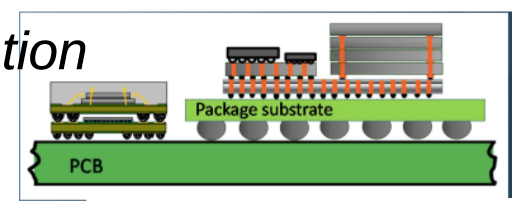


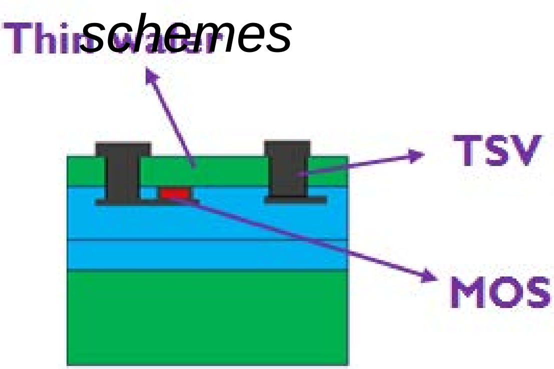

Side-by-side dice on an Interposer, also called “2.5D-IC”

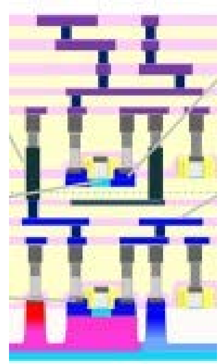
Vertically stacked dice, called “3D-IC”

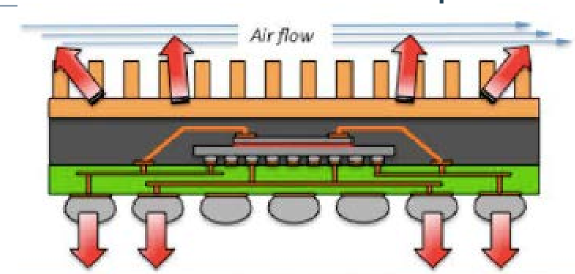
Source: YOLE http://www.i-micronews.com/lectureArticle.asp?id=8836





# Key Question and Goal

- RER-3D: A Research Center for Radiation Effects Reliability Mechanisms ***Unique to 3D Integration***
- *"**How does** the radiation response of complex **3D** integrated electronic systems (esp. intimately integrated) **differ from conventional planar electronics**, and how do we analyze it?"*
- …apply extensive expertise in radiation-effects mechanisms, modeling, and testing to identify and ***characterize the unique considerations of the geometries and materials in 3D integrated technologies*** using advanced simulation and novel experimental techniques.

*Focus on how the integration modifies what we know (don't know) about the response in "2D" – e.g. what is the "local environment"*

# RER3D: Superposition Strategy

*Dashed lines designate core tasks in this DTRA Project*

**Radiation** transport Modeling of 3D Integrated structure

**Testing** of constituent structures (low layer count, TSVs plus transistors, etc.)

**Conventional "2D"**

**Radiation** response

*Coupled*

**Thermal** response

**RER3D**

***Radiation Effects Reliability Mechanisms in 2.5/3D***

***Result:*** *Methods for characterization of integrated parts for Radiation Environments*

**Test** flight on small satellite

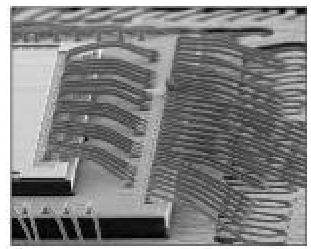
***Thermal****: This DTRA program will consider the potential temperature dependence of the radiation response*

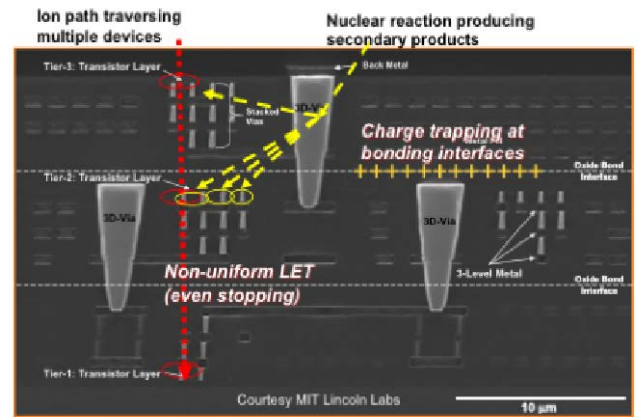
**Thermal** modeling and / or measurement of 3D Integrated structure

**Testing** of integrated structures using Aeropspace depth-profiling with pulsed X-ray, NSRL high energy testing

# Potential Radiation Effects

- Removal of packaging may reduce shielding
- Stacking, bond wires, interposers, TSVs can alter "local" internal radiation environments
  - *Attenuation*
  - *Enhancement*
  - *Secondary products*

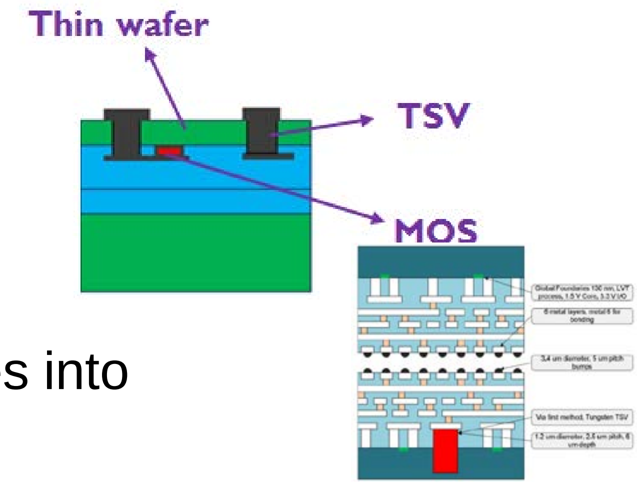




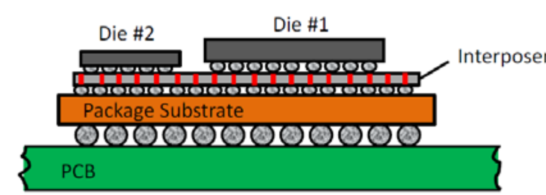

- New interfaces for charge trapping
- Thermal profiles in stacks may impact the radiation response
- Manifestations – multiple events in a 3D stack, becomes a 2D planar system analysis

# Approach

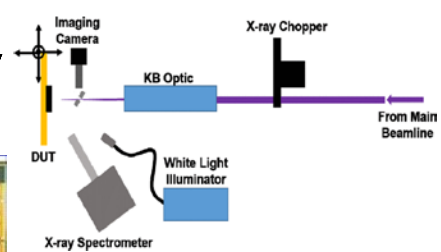
- Study at multiple levels of complexity
  - Baseline constituent structures
  - Basic circuit elements
  - Integrated functions



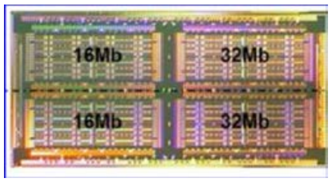

- Utilize CAD file formats to translate structures into radiation transport simulations
- Leverage existing knowledge about constituent technologies and circuits




- Identify do/don't cares, help guide priorities for applications
- Develop and apply models with increasing complexity program matures

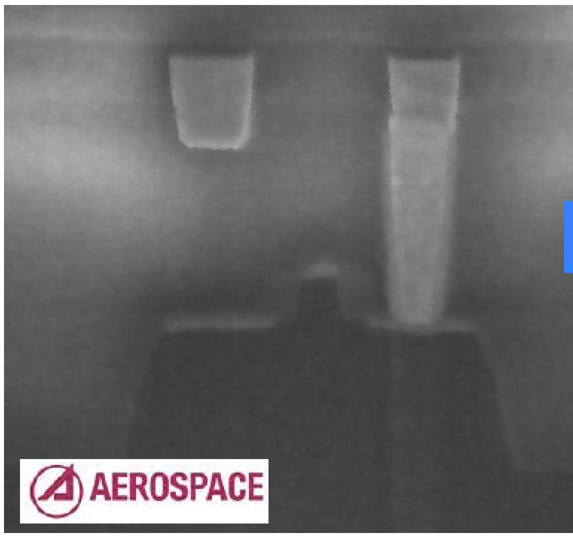



- Apply unique test capabilities

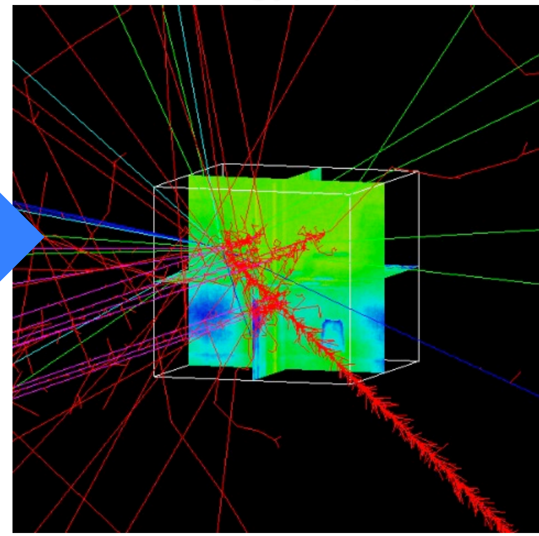


# Example: High-Z Materials and Single Events

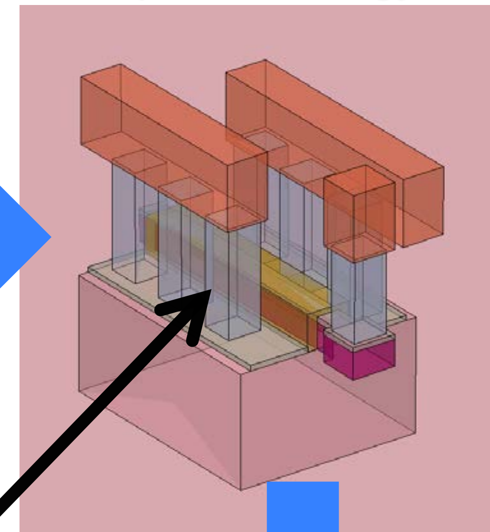
Device Image from Aerospace
(1 of 490 slices shown)

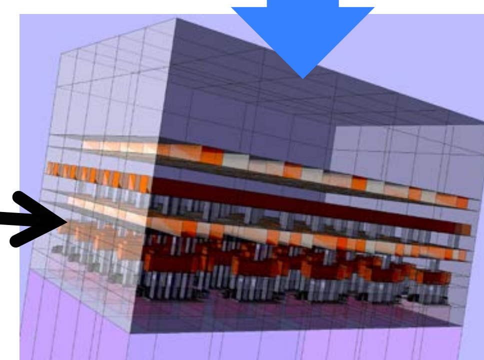



3D structural model created for MRED; simulate Single Event energy deposition



3D TCAD model created; simulated device response to deposited energy



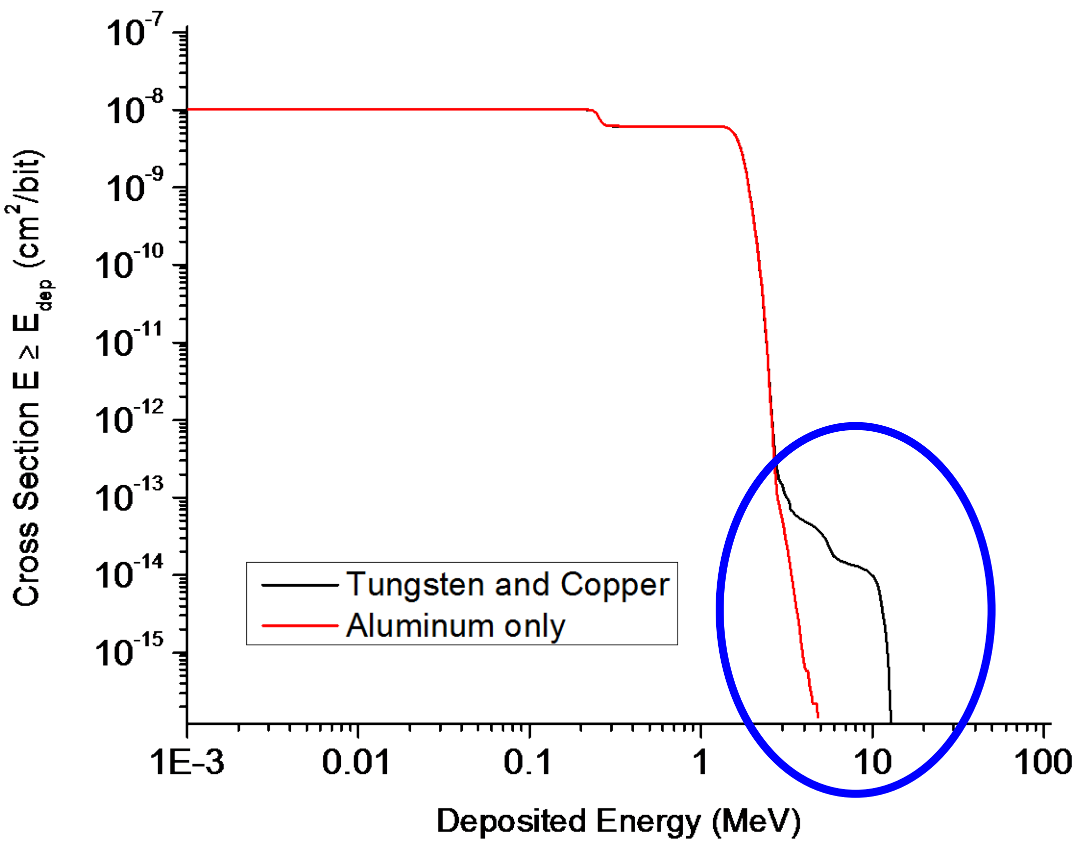


Simulate energy deposition and response for Al vs. W metal to look for possible single event enhancement

Cell arrayed in simulations to obtain statistics

*R. D. Schrimpf et al., MRQW 2011, supported by the AFOSR/AFRL HiRev Program*

# MRED Results – Fe Broadbeam

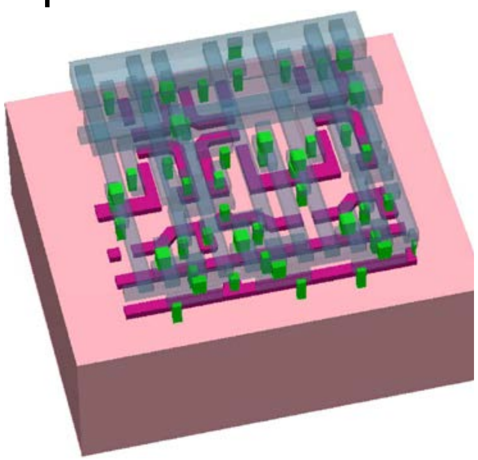


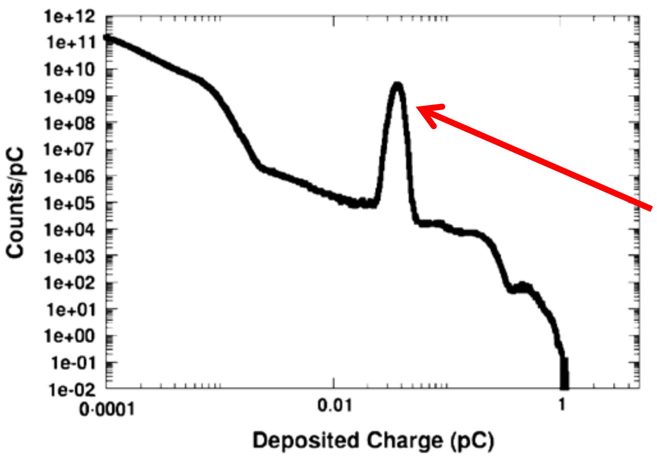

*R. D. Schrimpf et al., MRQW 2011, supported by the AFOSR/AFRL HiRev Program*

- 1 GeV $^{56}Fe$ – normal incidence to device surface
- 3 × 3 replication of base TCAD structure (reduce edge effects)
- 500 × $10^6$ events simulated
- Estimate probability of events with energy equal to or greater than a given energy ($E \geqq E_{dep}$)
- Presence of W and Cu impacts the maximum predicted energy deposition in the sensitive volume group (~ 2-3 × )

# Example: Manifestations

- Unexpected (based on the storage cell design) single-event upsets were observed in a memory part with less ionizing particles (lower LET) than expected thresholds
- Radiation transport analysis revealed that high-LET secondary products produced by interactions of the lighter particles with the high-Z metal interconnect plugs in the stack was responsible for the errors in question



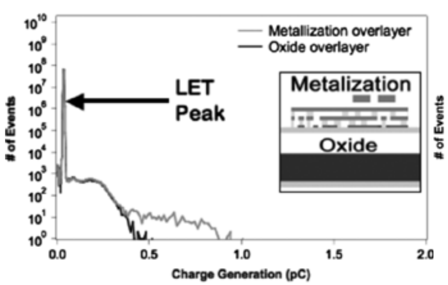


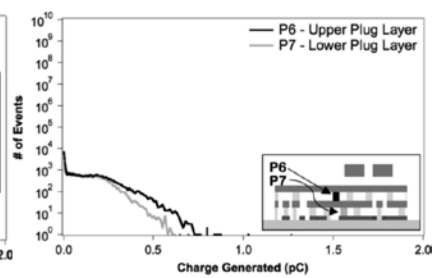

Simulated histogram of number of particles/pC versus deposited charge shows for **523 MeV $^{20}$Neon (average LET = 1.79 MeV-cm$^2$/mg)** shows a peak deposited charge at about 1.1 pC, **comparable to the amount of charge deposited by a primary ion with LET = 50 MeV-cm$^2$/mg** due to nuclear reactions in the high-Z over layer material

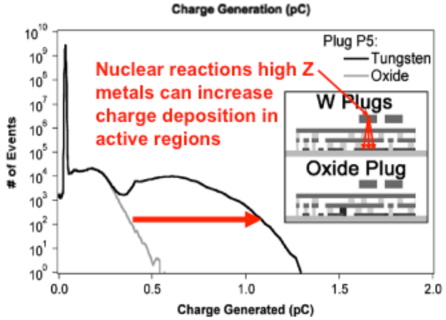
D. R. Ball, et al, Simulating Nuclear Events in a TCAD Model of a High-Density SEU Hardened SRAM Technology, *IEEE Trans. on Nucl. Sci.*, 53, 4, Aug. 2006, pp.1794-1798

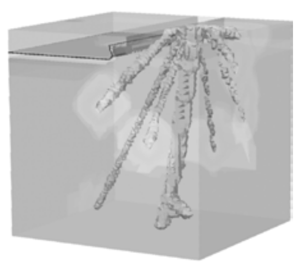
# Opportunity: TSV Structures

- Transport simulations used to study the impact of geometry and material on shielding and secondary production
- Wafers with transistors arrays *with and without TSV over layers* to be studied experimentally (from imec)

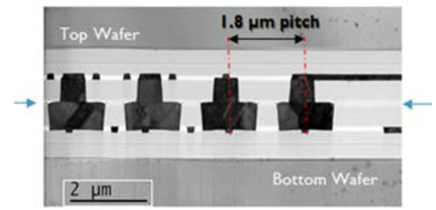


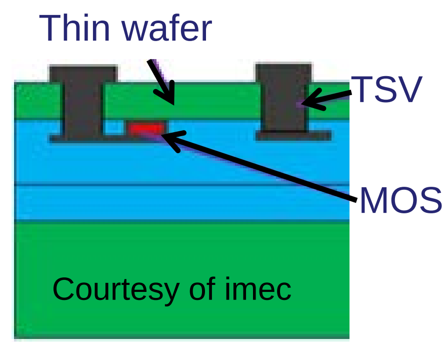



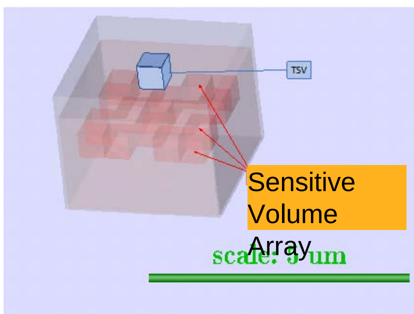



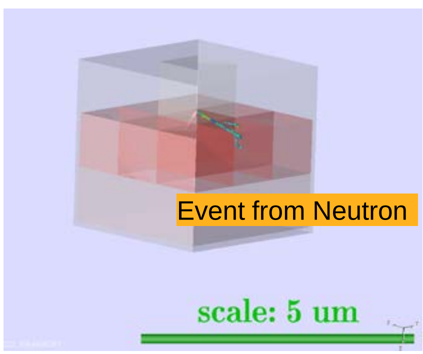



A. S. Kobayashi et al., The Effect of Metallization Layerson Single Event Susceptibility *IEEE Trans. on Nucl. Sci.*, 52, 6, Dec. 2005, pp. 2189-2193



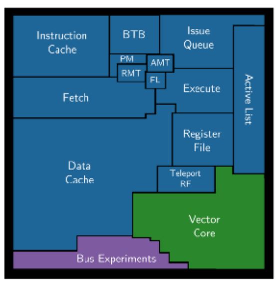



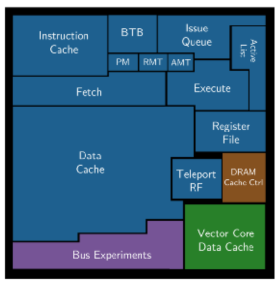
# Opportunity: Test Circuit (MPU)

2D and 3D versions of microprocessors of similar designs (NCSU)

- Both in IBM (now GF) 130 nm bulk CMOS
- Packaged with ~90 pins, mounted on daughter card on an FPGA board
- Develop code snippets that can signal presence of transient fault through data communicated via Dcache
- Run code snippets twice - compare data in Dcache for identical snippets. Use to count and (to some degree) locate transient fault when it occurs
- Compare against 2D version

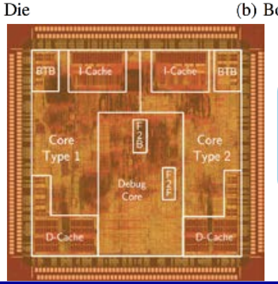


(a) Top Die



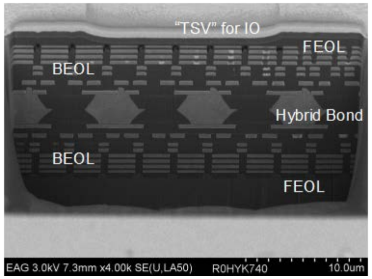
(b) Bottom Die

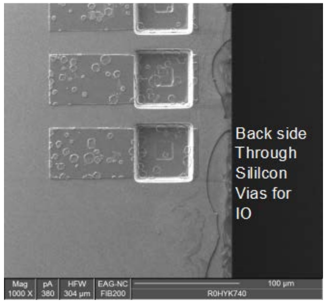
Die size: ~ 4 x 4 mm
Chip consists of multiple experiments:
- Heterogeneous multi-core processor (blue)
- Vector core (green)
- 3D F2F, F2B bus experiments (purple)
- DRAM cache controller (brown)

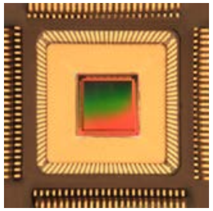


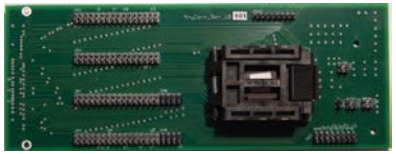

2D: 5 x 5 mm, no 3D features

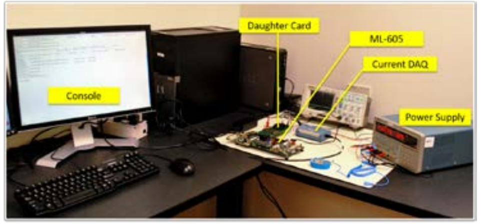
Wire bonded into package like that from 3D version







# Opportunity: Test Circuit (SRAM)

- 3D stack consisting of two 28 nm bulk CMOS layers with non-TSV interposer (NCSU)
- Tapeout : July or Oct.  Parts in 2019
- Hybrid face to face bonding
- Simple wet-etch TSVs
- Stack two 32k SRAMs : area : 0.25 sq.mm.
- Conduct march tests from BIST engine to capture time and location of bit flips
- Serialize this information out

# RER3D : Synergy / Tech Tansfer

- **DARPA** (UCLA and NCSU connections)
- **NASA** NEPP (VU Connections)
- **Industry** (ex VU students in industry, imec, Leti, and Enhanced Semi connections; other relationship through the NASA interactions
- **AMSAT** potential collaborator for small satellite launch opportunity which could include a 3DIC in-fight radiation experiment. VU has a demonstrated history and ongoing efforts in cube/small satellite payloads for rad-effects experiments.
- **Technology Transfer Potential**: methods for characterization of parts for space (NASA, DoD, commercial space) missions and nuclear environments; understanding of SE mechanisms in terrestrial environments

# Workforce Development

- Student visits among team facilities have been very beneficial in previous DTRA programs
- In this program, we will have an intentional focus on "cross training" of students
  - Internships (esp. @ imec, cea-Leti, Aerospace Corp.)
  - "Exchange" visits with other universities
    - Collaborative testing
    - Spending a month, semester, etc. at partner universities